

# A New Binary Inductive Divider Comparator System for Measuring High-Voltage Thermal Converters

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**Abstract**—National Measurement Institutes have traditionally used bootstrapping or build-up techniques to determine the ac-dc difference of high-voltage thermal converters (HVTs) in terms of the ac-dc difference of lower-voltage converters. We describe a method of determining the ac-dc difference of HVTs that is independent of the build-up process. A description of the system and technique is given and preliminary data is presented.

**Index Terms**—AC-DC difference, high-voltage thermal converters (HVTs), inductive divider, thermal converter, thermal voltage converters (TVC).

## I. INTRODUCTION

HIGH-VOLTAGE thermal converters (HVTs) are used as standards of ac-dc difference and for the measurement and calibration of ac voltage up to 1000 V and 100 kHz [1]. A build-up or scaling procedure is generally employed to determine the ac-dc differences of these devices. In the build-up process (shown in Fig. 1) the ac-dc difference of an HVT is determined by comparison against a thermal converter of a lower voltage rating. If the ac-dc difference of the higher-range HVT is independent of voltage level, this comparison will provide the ac-dc difference of the higher-range HVT, to within the measurement uncertainty. However, the ac-dc difference of the multiplying resistors used in HVTs may vary as a function of input voltage level, creating significant errors in the build-up process. Formal and informal international intercomparisons of HVTs have revealed variations among the participant laboratories [2], [3]. Therefore, some National Measurement Institutes (NMIs) are developing calibration procedures that are independent of the build-up process [4]–[6]. In this paper, we report an independent method for determining the ac-dc differences of an HVT based on a binary inductive voltage divider (BIVD) [7]. We plan to use this independent approach in addition to the traditional build-up method to maintain the quality of the National Institute of Standards and Technology (NIST) HVTs.

## II. BIVD CONSTRUCTION AND CALIBRATION

The BIVD consists of 240 turns of 0.52 mm<sup>2</sup> twisted-pair wire wound around a high permeability core of 4.2 cm<sup>2</sup> cross-sectional area, connected to form a center-tapped divider. This winding technique provides good symmetry and a well-defined

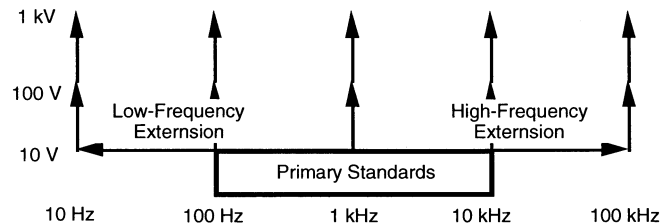


Fig. 1. Build-up diagram for characterizing HVTs, beginning with the primary standards at 5 to 10 V and continuing up to 1 kV. The BIVD comparator is intended to address the process indicated by the vertical arrows.

TABLE I  
CENTER-TAP ERROR (PARTS IN 10<sup>6</sup>) OF THE BIVD AS A FUNCTION OF THE APPLIED VOLTAGE AND FREQUENCY. THE MEASUREMENT UNCERTAINTY IS ESTIMATED TO BE LESS THAN  $0.5 \times 10^{-6}$

Frequency (kHz)	Voltage 100 V	Voltage 50 V
1	0.1	0.1
10	0.1	0.1
20	0.6	0.5

center tap ratio. There are two layers of windings with an intermediate layer of a glass tape to provide a greater distance between turns and thus reduce the capacitance of the transformer. The transformer is enclosed in a shielded box with type-874 connectors. The BIVD is designed to operate at 1000 V up to 50-kHz and to present impedances of less than 200 k at frequencies up to 50 kHz.

The accuracy of the center tap of the BIVD was tested in a bridge configuration against a decade inductive voltage divider set to the ratio 0.5. Since the BIVD is used in TVC measurements with one side of the input grounded, the bridge voltage source was grounded and an isolation transformer was used to allow the detector to be grounded as well. The tests were performed by interchanging the input leads on the dividers. The test results are summarized in Table I. The errors in the BIVD are very small compared to the uncertainties of the HVT build-up process.

## III. BIVD COMPARATOR SYSTEM

The comparator system compares the ac-dc differences of two thermal voltage converters (TVCs) to the ratio of a BIVD (although the system is intended for use with HVTs, TVCs of any voltage ranges may be used, as long as the ranges are roughly 2:1). The comparison requires that the BIVD ratio and the ratio of two high-voltage dc sources be known. The two HVTs measure the rms voltages of two high-voltage ac sources in terms of the dc sources. The ratio of the ac sources is also determined

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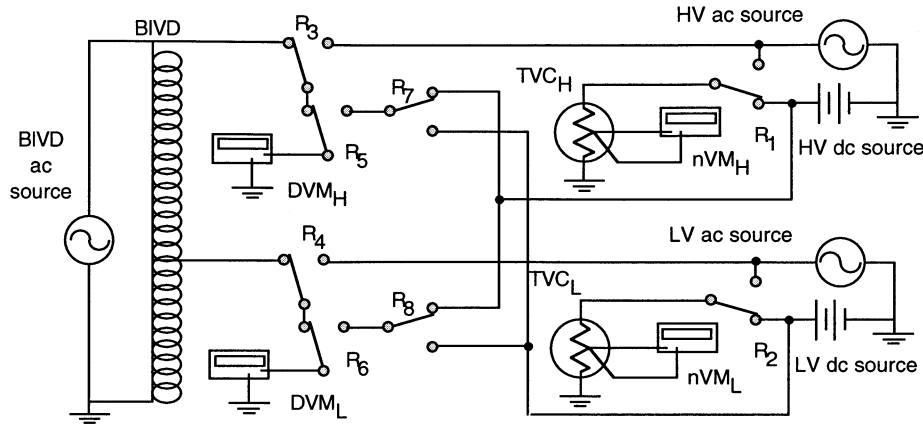


Fig. 2. Schematic of BIVD comparator system.

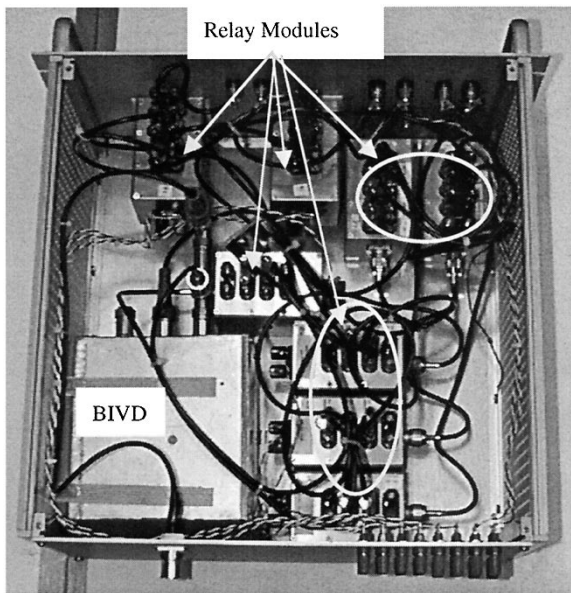


Fig. 3. Interior view of the BIVD comparator enclosure.

in terms of the ratio of the BIVD by the use of two high-performance digital voltmeters (DVMs) that are used solely as transfer instruments. The calibration of the DVMs is therefore not required for the measurement process, as the process relies only on the linearity of the voltmeters over a limited voltage range.

A schematic of the comparator system is shown in Fig. 2 and a picture in Fig. 3. A previous prototype of the comparator system [8] featured eight relays spread out across a bench. In the new version of the BIVD comparator system, the eight relays are contained in a shielded enclosure, along with the inductive divider itself.

The measurement sequence is as follows.

- 1) The two HVTs are connected simultaneously to the high-voltage (TVC<sub>H</sub>) and low-voltage (TVC<sub>L</sub>) dc sources while the DVMs are connected to the top of the BIVD (DVM<sub>H</sub>) and its center tap (DVM<sub>L</sub>). The BIVD voltage is supplied by an ac source. The two HVT outputs are monitored by nanovoltmeters (nVM<sub>H</sub> and nVM<sub>L</sub>). The circuit diagram for this measurement phase

is shown in Fig. 4. All system grounds are actually terminated at the ac source supplying the BIVD.

- 2) After the nanovoltmeters and high-voltage DVMs are read, relays  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$  are switched so that ac voltage is supplied to the HVTs and the DVMs are connected to the high- and low-voltage ac sources. In this configuration, the ratios of the high- and low-voltage ac voltages are determined in terms of the BIVD center tap ratio. A schematic of this configuration is shown in Fig. 5. While the relays are in these positions, the polarities of the dc voltages are reversed at the sources.
- 3) After the nanovoltmeters and high-voltage DVMs are read, relays  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$  are returned to their initial positions (Fig. 4). The measurement proceeds as in Step 1, except that the dc voltage is of the opposite polarity. Steps 1, 2, and 3 determine the ratio of the ac sources in terms of the ratio of the dc sources (which are generally more stable) and also determine the ac-dc differences of the two HVTs.
- 4) After repeated cycles of the measurements discussed in Steps 1–3, relays  $R_5$  and  $R_6$  are closed to connect both DVMs to the high-voltage dc source, as shown in Fig. 6. DVM readings are taken while both polarities of dc voltage are applied to the DVMs. Relays  $R_7$  and  $R_8$  are then switched to connect both DVMs to the low-voltage dc source and readings are taken while both polarities of dc voltage are applied to the DVMs. This procedure determines the departure from the nominal ratio of the DVMs.

Neglecting small second-order quantities, the relationship between the ac-dc differences of the higher voltage converter,  $\delta_H$  and the lower voltage converter,  $\delta_L$ , may be given in the form

$$\delta_H - \delta_L = \Delta ratio_{ac} - \Delta ratio_{dc} - \delta_H^m + \delta_L^m. \quad (1)$$

In (1),  $\Delta ratio_{ac}$  is the departure of the ac from nominal ratio as determined by the BIVD, satisfying the equation

$$\frac{ac_H}{ac_L} = 2(1 + \Delta ratio_{ac})$$

where  $ac_H$  is the average voltage supplied by the high-voltage ac source, as determined by the high-voltage DVM and  $ac_L$  is the average voltage supplied by the low-voltage ac source, as

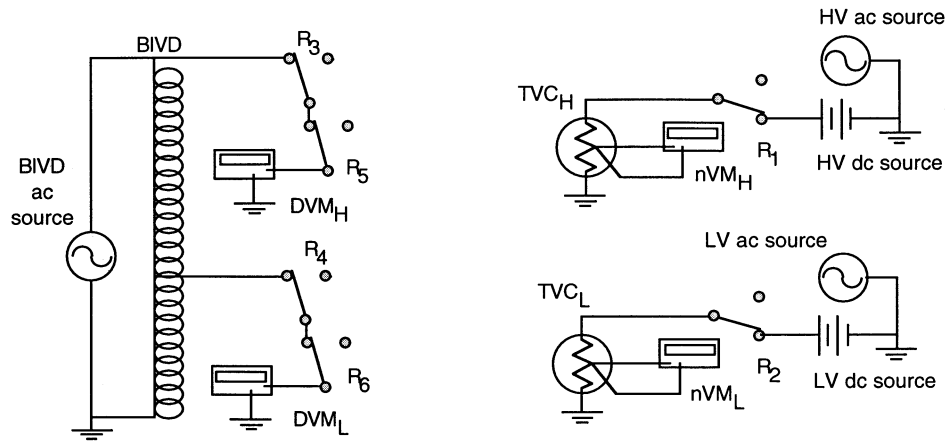


Fig. 4. Circuit diagram of the comparator system while dc voltage is applied to the thermal converters.  $DVM_H$  and  $DVM_L$  are connected to the BIVD.

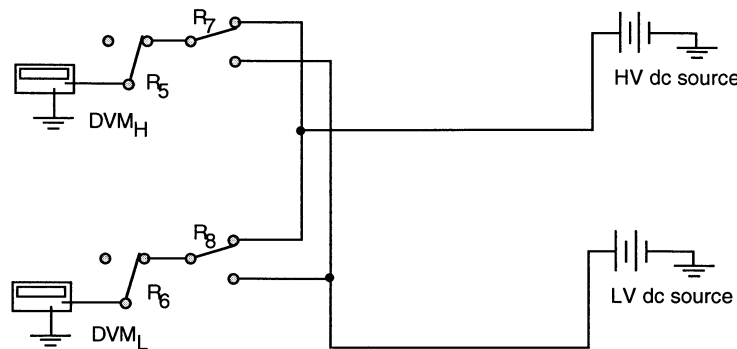


Fig. 5. Circuit diagram of the comparator system while ac voltage is supplied to the thermal converters.  $DVM_H$  and  $DVM_L$  are also connected to the ac sources.

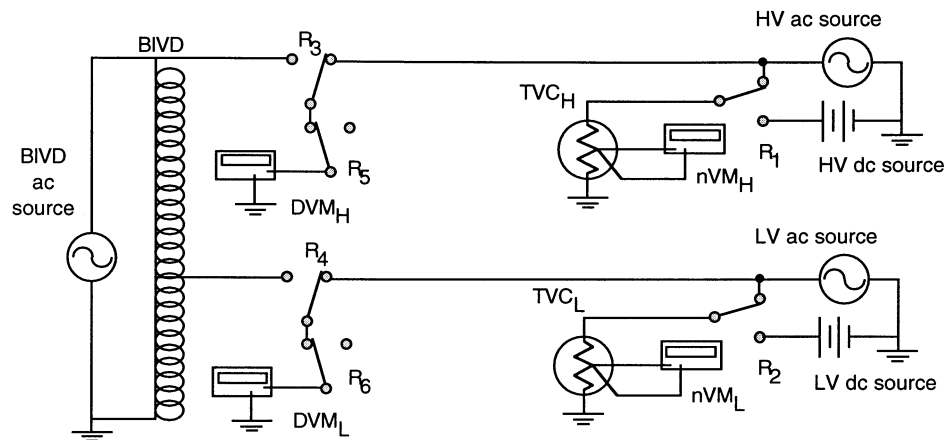


Fig. 6. Circuit diagram of the comparator system with the DVMs connected to the high-voltage dc sources. When the DVMs are connected to the low-voltage dc source,  $R_7$  and  $R_8$  are in the normally open position.

TABLE II  
PRELIMINARY ESTIMATE OF BIVD UNCERTAINTIES IN  $\mu V/V$

Type A component	3.3
Dc measurement	1.2
BIVD ratio	1.2
Loading	1.2
RSS	3.9
Expanded uncertainty ( $k = 2$ )	7.8

determined by the low-voltage DVM in measurement step 2.

Similarly,  $\Delta ratio_{dc}$  denotes the departure of dc from nominal ratio, satisfying the equation

$$\frac{dc_H}{dc_L} = 2(1 + \Delta ratio_{dc})$$

where  $dc_H$  is the average value of both polarities of the dc voltage supplied by the high-voltage dc source and  $dc_L$  is the average value of both polarities of the dc voltage supplied by the low-voltage dc source, as determined in measurement step 4. In addition,  $\delta_H^m$  is defined by  $\delta_H^m = (E_{ac} - E_{dc})/(n_H E_{dc})$ ,

TABLE III  
COMPARISON BETWEEN RESULTS ( $\delta$ ) OBTAINED FROM THE TRADITIONAL BUILD-UP PROCESS AND RESULTS OBTAINED USING THE BIVD COMPARATOR SYSTEM IN  $\mu\text{V/V}$ . UNCERTAINTIES ARE FOR  $k = 2$

Test (High)	Test TVC Range	Standard (Low)	Standard TVC Range	$\delta$ From Build-up	$\delta$ From BIVD	$\delta$ From Build-up	$\delta$ From BIVD
TVC	V	TVC	V	10 kHz		20 kHz	
F <sub>7</sub> 600-F <sub>7</sub> 2	600	F <sub>1</sub> 300-FB	300	-1.3 $\pm$ 10.4	-4.3 $\pm$ 7.8	-6.0 $\pm$ 11.0	-9.2 $\pm$ 7.8
				20 kHz		50 kHz	
F <sub>7</sub> 200-F <sub>7</sub> 2	200	F <sub>1</sub> 100-FB	100	-0.7 $\pm$ 7.7	+2.1 $\pm$ 7.8	-2.8 $\pm$ 9.0	-0.7 $\pm$ 7.8

where  $E_{ac}$  is the high-voltage TVC output with ac applied,  $E_{dc}$  the output of this TVC with dc applied and  $n_H$  the TVC response characteristic. Similarly,  $\delta_L^m$  is defined by  $\delta_L^m = (E_{ac} - E_{dc})/(n_L E_{dc})$  where  $E_{ac}$  is the low-voltage TVC output with ac applied,  $E_{dc}$  the output of this TVC with dc applied and  $n_L$  the TVC response characteristic.

#### IV. LOADING COMPENSATION

An error in the BIVD ratio of about  $10^{-4}$  at 20 kHz results from the loading at the center tap due to the impedance of the system connections and DVM input. To compensate for this error, a simple RC network was installed between the BIVD top high terminal and the center tap high terminal. The appropriate compensation capacitance was estimated by assembling a bridge circuit in order to balance the loading. The loading error was reduced to  $10^{-6}$  using a network with about 700-pF in parallel with 1 M. Other measurement frequencies require different values of RC.

#### V. RESULTS

Table II gives the contributions to the estimated uncertainty for the BIVD comparator system. Table III presents data taken with the BIVD system compared to the ac-dc differences of several HVTCs predicted from build-up measurements. The BIVD results compare favorably with the results from the build-up process, increasing our confidence in both the traditional build-up process and in the design and construction of the NIST high-voltage resistors.

#### VI. CONCLUSIONS AND FUTURE PLANS

We have demonstrated a comparator system for determining the ac-dc difference of HVTCs independent of the traditional build-up process. Preliminary data show that results from the BIVD comparator are in good agreement with those from the voltage build-up process and provide an independent confirmation of the efficacy of the build-up technique. Future plans include extending the applied voltage to 1000 V and extending the measurement frequency to higher values at these voltages.

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